Doping Optimization for High Efficiency in Semiconductor Diode Lasers and Amplifiers

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***Abstract*—A generalized theoretical formalism is derived that optimizes the doping profile of semiconductor diode lasers and amplifiers for maximum power conversion efficiency by balancing resistive and free-carrier absorption losses. The doping profile is shown to be the same function of optical mode profile, free-carrier absorption cross-section, and carrier mobility, independent of the specific model used for efficiency. The magnitude of the doping is dictated by the chosen efficiency model and the device design and operating conditions. The derived formalism can be applied to any particular model of diode emitter efficiency and expressed entirely in terms of measurable parameters. In addition, as a consequence of this analysis, a figure of merit is introduced that quantifies the ability of a waveguide to perform as a high efficiency laser or amplifier.**

***Index Terms*—Diode lasers, semiconductor lasers, semiconductor optical amplifiers.**

I. Introduction

ELECTRICALLY injected diode lasers have been demonstrated in many compound semiconductor material systems, including GaAs, InP, GaSb, and GaN, to realize coherent light emitters with frequencies ranging from the ultraviolet to the mid-infrared. Consequently, diode lasers have become widely utilized in applications including communications, imaging, remote sensing, displays, manufacturing, and healthcare. For all of these application areas, there is a consistent demand for higher-power and higher-wallplug-efficiency lasers to improve system performance. There have been a multitude of approaches taken to improve device efficiency with significant advances occurring in the 0.78–1.06 μm regime ([1] and references therein) and, more recently, at 1.53 μm [2].

Nevertheless, there has been little investigation into the systematic optimization of doping for high efficiency. Kanskar *et al.* suggested an approach for reducing resistive and optical absorption losses by utilizing a particular doping profile dictated by modal and material properties [3]. However, the approach taken did not directly attempt to maximize the power conversion efficiency (PCE) and is very specifically applicable only to the case considered where the absolute resistive and absorption losses are minimized. Moreover, many researchers have recognized the potential for efficiency improvement through the use of asymmetric waveguides [4], [5], [6], which reduce series resistance and free-carrier absorption (FCA) by limiting the amount of p-doped material. Still, to date there has been no general metric by which one can determine the relative improvement provided by these design changes prior to full device modeling.

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In this paper, a general formalism is derived that prescribes an optimal doping profile for maximizing diode laser and amplifier PCE. The approach is based on maximizing a generic PCE function, which is implicitly dependent on FCA and series resistance. This provides the general doping profile required for optimal PCE. With a particular PCE expression and operating condition, it is possible then to determine the level of doping required for peak efficiency. Moreover, this formalism provides a figure of merit by which the "quality" of a waveguide can be determined prior to any further design or device modeling. Specifically, this means there is a metric by which one can measure the improvement provided by asymmetry or any other waveguide design changes that ultimately influence optical loss and series resistance.

II. Generalized Expression

As discussed, a performance metric of primary interest for diode lasers and amplifiers is the PCE, $\eta_{PCE} = P_{out}/P_{in}$. The electrical power supplied to the device is $P_{in} = IV$, where I and V are the externally supplied current and voltage, respectively. In general, the current-voltage relationship of these diodes has an ohmic contribution, where some fraction of the supplied voltage is related to the current by a series resistance (R_s). P_{out} is the (net) optical power emitted by the device, and it can be a complicated function of a number of parameters. However, the parameter of interest here, due to its relationship to the doping, is the FCA contribution to the intrinsic optical loss (α_i). Thus, it is clear that PCE is implicitly dependent on R_s and α_i, *i.e.*, the function is $\eta_{PCE}(\alpha_i, R_s)$, and this is the only condition required to proceed to the doping optimization analysis.

A. Derivation

As just described, the expression for semiconductor diode laser and amplifier PCE is some (for now, unspecified) function of α_i and R_s, written here as a function f:

$$\eta_{PCE} = f\left(\alpha_i\left[N\left(y\right)\right], R_s\left[N\left(y\right)\right]\right). \quad (1)$$

In the above expression, α_i and R_s are taken to be functionals of the transverse doping concentration profile, $N(y)$. The contribution to α_i from FCA [7] and R_s from waveguide resistance [8] are dependent on the transverse doping and are expressible as:

$$\alpha_i\left[N\left(y\right)\right] = \int_a^b \left|\phi\left(y\right)\right|^2 \sigma\left(y\right) N\left(y\right) dy, \quad (2)$$

$$R_s\left[N\left(y\right)\right] = \int_a^b \frac{1}{qA\mu\left(y\right) N\left(y\right)} dy, \quad (3)$$

where a and b are the limits of integration over the waveguide region of interest, $\phi(y)$ is the normalized optical mode profile (*i.e.*, $\int |\phi(y)|^2 dy = 1$), $\sigma(y)$ is the FCA cross-section, $\mu(y)$ is the carrier mobility, A is the area of electrical injection, and q is the elementary charge constant. As will be seen in an upcoming section, contributions to α_i and R_s from sources other than FCA and waveguide resistance, respectively, can be included in the model, although they do not affect the result of this general analysis.

According to the calculus of variations [9], [10], the extremal function of the PCE, *i.e.*, the $N(y)$ that maximizes η_{PCE}, can be found by taking the first variation of (1). Written mathematically it is

$$\lim_{\epsilon\to 0} \frac{d}{d\epsilon} f\left(\alpha_i\left[N(y)+\epsilon\eta(y)\right], R_s\left[N(y)+\epsilon\eta(y)\right]\right) = 0. \quad (4)$$

where $\eta(y)$ is an arbitrary function that vanishes at the integral endpoints. By applying the chain rule for the derivative with respect to ϵ, it is found that

$$\lim_{\epsilon\to 0}\left[\frac{\partial f}{\partial \alpha_i}\frac{d\alpha_i}{d\epsilon} + \frac{\partial f}{\partial R_s}\frac{dR_s}{d\epsilon}\right] = 0. \quad (5)$$

Using (2) and (3) to determine the derivatives yields

$$\int_a^b \eta(y)\left[\frac{\partial f}{\partial \alpha_i}|\phi(y)|^2\sigma(y) - \frac{\partial f}{\partial R_s}\frac{1}{qA\mu(y)\left(N(y)\right)^2}\right]dy = 0. \quad (6)$$

In the above equation, the expression in square brackets must be equal to zero, and so

$$N(y) = C\sqrt{\frac{1}{|\phi(y)|^2\sigma(y)\mu(y)}}, \quad (7)$$

where

$$C = \sqrt{\frac{1}{qA}\frac{\partial f/\partial R_s}{\partial f/\partial \alpha_i}}. \quad (8)$$

This brings one to the first important result of this analysis: the optimal doping profile for maximizing PCE is always proportional to $\left[|\phi(y)|^2\sigma(y)\mu(y)\right]^{-1/2}$. This is in agreement with the results of Kanskar *et al.* [3], although the formalism derived here is more generally applicable because it does not inherently depend on the particular efficiency model. In fact, the result from Kanskar *et al.* can be directly derived from the formalism just introduced, as will be shown in an upcoming section. The universal nature of this result is true for any model that expresses the optimization metric as represented in (1).

Although the result in (7) is not intuitively apparent, it does make good sense. In essence, the expression indicates that doping should be reduced wherever it is less favorable or less necessary, *i.e.*, where optical field and absorption cross-section are large or mobility is high.

B. Doping Level and Waveguide Figure of Merit

In order to determine the appropriate magnitude of the doping for a particular f, it is necessary to solve for the constant C. This can be done by inserting into (8) the expressions for $\partial f/\partial R_s$ and $\partial f/\partial \alpha_i$, which generally is dependent on R_s and α_i. Again utilizing the definitions in (2) and (3) along with the solution in (7), it is found that

$$\alpha_i = C\kappa_0, \quad (9)$$

$$R_s = \frac{1}{qA}\frac{\kappa_0}{C}, \quad (10)$$

where

$$\kappa_0 = \int_a^b \sqrt{\frac{|\phi(y)|^2\sigma(y)}{\mu(y)}}dy. \quad (11)$$

From (8)–(10) comes the constant C, which specifies the magnitude of the doping that maximizes the PCE for a particular PCE definition f.

It can be seen from (9) and (10) that, for the optimized doping profile, the α_i and R_s are linearly dependent on the constant κ_0. It is well known that lower α_i and R_s should result in higher PCE. Consequently, waveguide designs with lower κ_0 will tend to be, *a priori*, better candidates for high efficiency. Thus, one finds the second important conclusion from this formalism: κ_0 in (11) is a figure of merit that gives a measure of whether changes to a waveguide design will tend to improve PCE.

An after-the-fact inspection of the definition of κ_0 reveals that it makes intuitive sense; it is essentially a measure of the overlap between the optical mode profile and the FCA cross-section and carrier mobility. In order to keep κ_0 small (and thus keep α_i and R_s small), the goal is to have low overlap between the mode and high FCA cross-section areas and high overlap between the mode and high mobility areas. This says then that the mode should be contained in material where carrier transport is good and FCA is low. In other words, κ_0 describes with mathematical certainty why asymmetric waveguides with lower overlap between the optical mode and p-material should have higher PCE than conventional symmetric structures. Moreover, the quantitative nature of κ_0 goes beyond the qualitative intuitive understanding of waveguide design and could therefore aid in the optimization of waveguides for high-efficiency semiconductor lasers and amplifiers.

III. Semiconductor Lasers

It is instructive to investigate some specific cases of PCE definitions and the trends associated with optimized doping. To begin, a couple of basic models of laser PCE will be discussed.

Above the threshold current ($I > I_{th}$), the output power of a diode laser increases linearly with current, as is conventionally given by [11]

$$P_{out} = \eta_i V_{ph}\frac{\alpha_m}{\alpha_m+\alpha_i}\left(I - I_{th}\right), \quad (12)$$

where η_i is the internal quantum efficiency, V_{ph} is the voltage associated with the energy of a single photon, and $\alpha_m = 1/(2L)\ln(1/R_1R_2)$ is the mirror loss for a cavity of length L

formed by mirrors with reflectivities R_1 and R_2. The current-voltage characteristic is also a linear function when operating above the turn-on voltage (V_0), so that the electrical power supplied to the laser is

$$P_{in} = I\left(V_0 + IR_s\right). \tag{13}$$

The PCE is then the ratio of these two quantities.

A. Optimizing for Different Operating Conditions

1) High Current: The first case to be considered is when the doping is optimized for a particular current well above I_{th}. This case is typically useful for high-power lasers, such as broad-area devices used as pump sources for solid-state lasers. Directly inserting (12) and (13) into the definition for PCE results in

$$\begin{aligned}\eta_{PCE} &= \frac{\eta_i V_{ph}\alpha_m\left(I - I_{th}\right)}{I\left(V_0 + IR_s\right)\left(\alpha_m + \alpha_i\right)} \\ &\approx \frac{\eta_i V_{ph}\alpha_m}{\left(V_0 + IR_s\right)\left(\alpha_m + \alpha_i\right)},\end{aligned} \tag{14}$$

where the approximation of the second line assumes that the operating point is such that $I \gg I_{th}$. The above expression is the definition of the function f, whose value is to be maximized. The partial derivatives required to solve for C in (8) are

$$\frac{\partial f}{\partial \alpha_i} = -\frac{\eta_i V_{ph}\alpha_m}{\left(V_0 + IR_s\right)\left(\alpha_m + \alpha_i\right)^2}, \tag{15}$$

$$\frac{\partial f}{\partial R_s} = -\frac{\eta_i V_{ph}\alpha_m I}{\left(V_0 + IR_s\right)^2\left(\alpha_m + \alpha_i\right)}. \tag{16}$$

Replacing α_i and R_s in these expressions with their respective optimal values in (9) and (10) and plugging that information into the equation for C yields

$$C^2 = \frac{1}{qA}\frac{\left(\alpha_m + C\kappa_0\right)I}{V_0 + I\kappa_0/\left(qAC\right)}. \tag{17}$$

In this case the equation has a closed-form solution:

$$C = \sqrt{\frac{\alpha_m I}{qAV_0}}. \tag{18}$$

Although similar, this result has several important differences when compared to the previously derived expression by Kanskar *et al.* In particular, the expression they attempt to minimize is the total loss:

$$f = P_{loss} = P_o L\alpha_i + I^2 R_s, \tag{19}$$

where P_o is the average optical power in the laser cavity. Thus, they use absolute power lost rather than the ratio of the lost power to the total input power, *i.e.*, they minimize an absolute magnitude rather than maximize an efficiency. In general, this could be a negligible detail; however, for certain cases such as $V_0 \gg V_{ph}$, the difference could be significant, since (19) does not consider the defect voltage associated with V_0 whereas (14) does. Moreover, the P_o term is dependent on I, so one must be careful to ensure the values of these two terms are consistent. In particular, $P_o = P_{out}/\alpha_m L = \eta_i V_{ph}\left(I - I_{th}\right)/\left(\alpha_m + \alpha_i\right)L$. Nevertheless, by using the analysis of the previous section and (19), the constant defined as C for the analysis in Kanskar *et al.* is

$$C = \sqrt{\frac{I^2}{qAP_oL}}, \tag{20}$$

which is consistent with their result when their optical mode field is appropriately normalized. As will be explored in an upcoming section, this expression gives reasonably similar results, but it is not generally convenient for optimization under specific operating conditions.

2) Peak PCE: The other case considered here is optimization for the peak PCE operating point. This is useful for applications where efficiency is much more important than power, such as some communications applications. Bour and Rosen provided an expression for the maximum PCE of a diode laser, given as [12]

$$\eta_{PCE} = \eta_i\frac{V_{ph}}{V_0}\frac{\alpha_m}{\alpha_m + \alpha_i}\frac{x}{\left(1 + \sqrt{1 + x}\right)^2}, \tag{21}$$

where $x = V_0/R_s I_{th}$. The corresponding operating current and power are, respectively,

$$I = I_{th}\left(1 + \sqrt{1 + x}\right), \tag{22}$$

$$P_{out} = \eta_i V_{ph}\frac{\alpha_m}{\alpha_m + \alpha_i}I_{th}\sqrt{1 + x}. \tag{23}$$

Following the same procedure as in the preceding subsection, the solution for C can be found by solving the third-order polynomial equation

$$\kappa_0 C^2\left(\kappa_0 I_{th} + qAV_0C\right) - \left(\alpha_m + \kappa_0 C\right)^2 I_{th} = 0. \tag{24}$$

Although an explicit solution for C is not apparent, it is significant to note that the doping magnitude in this case is not only dependent on A, V_0, and α_m, but it is also a function of I_{th} and κ_0.

B. Performance Constraints

In general, the total intrinsic loss and series resistance will not depend solely on the doped material. For example, it is usual to expect contributions to α_i from scattering and to R_s from contacts and the device substrate or packaging. In this case, α_i and R_s can be replaced by terms that incorporate these other contributions, *i.e.*, $\alpha_i\left[N\left(y\right)\right] \to \alpha_i\left[N\left(y\right)\right] + \alpha_c$ and $R_s\left[N\left(y\right)\right] \to R_s\left[N\left(y\right)\right] + R_c$. Here it is assumed that the additional contributions are constant and represented by α_c and R_c.

Running through the high current case once more, one arrives at the doping level

$$C = \sqrt{\frac{\left(\alpha_m + \alpha_c\right)I}{qA\left(V_0 + IR_c\right)}}. \tag{25}$$

This is quite similar to the expression in (18). The primary difference is that the doping magnitude is now also influenced by the α_c and R_c terms. It is dependent on these in such a way that doping increases as α_c grows or R_c reduces. This suggests that the doping should be adjusted in a way that has the greatest impact, *e.g.*, if there is already some large α_c, it is

much more beneficial to take a slightly greater penalty in FCA loss and save more resistive power by increasing the doping.

Finally, for completeness, the polynomial equation for C in the peak PCE case with α_c and R_c is

$$\left(\kappa_0 C + qAR_c C^2\right)\sqrt{\left(\frac{\kappa_0}{qAC}+R_c\right)I_{th}+V_0} - \left(\alpha_m+\alpha_c+\kappa_0 C\right)\sqrt{\left(\frac{\kappa_0}{qAC}+R_c\right)I_{th}} = 0. \quad (26)$$

IV. Semiconductor Optical Amplifiers

This section will briefly outline the utility of the derived formalism for application to semiconductor optical amplifiers (SOAs). In general, the optimization procedure for any case follows closely that of the previous section.

The optical power along the length of an optical amplifier is typically described using the following differential equation:

$$\frac{dP}{dz} = \left(\Gamma g\left(n\right) - \alpha_i\right)P, \quad (27)$$

where Γ is the confinement factor of the mode to the active region and g is the material gain, a function of the active region carrier density n. Following a procedure similar to that in [13], the gain can be approximated as a linear function of current such that $g\left(n\right) = \eta_i \frac{V_{ph}}{\Gamma PL}\left(I - I_0\right)$, where I_0 is the transparency current. Inserting this into the above differential equation,

$$\begin{aligned} P_{out} &= P_0 e^{-\alpha_i L} + \left(1 - e^{-\alpha_i L}\right)\frac{\eta_i V_{ph}}{\alpha_i L}\left(I - I_0\right) \quad (28)\\ &\approx \eta_i V_{ph}\frac{\left(1-e^{-\alpha_i L}\right)}{\alpha_i L} I, \end{aligned}$$

where the approximation of the second line assumes $I \gg I_0$ and the optical input power, P_0, is negligible compared to P_{out}. Utilizing the same definition for P_{in} as presented previously, the PCE definition becomes

$$\eta_{PCE} = \frac{\left(1-e^{-\alpha_i L}\right)\eta_i V_{ph}}{\alpha_i L\left(V_0 + IR_s\right)}. \quad (29)$$

As before, in order to determine the doping magnitude, it is necessary to solve for the constant C. The required partial derivatives are

$$\frac{\partial f}{\partial \alpha_i} = -\frac{\eta_i V_{ph}\left(1 - e^{-\alpha_i L} - \alpha_i L e^{-\alpha_i L}\right)}{\alpha_i^2 L\left(V_0 + IR_s\right)}, \quad (30)$$

$$\frac{\partial f}{\partial R_s} = -\frac{\left(1-e^{-\alpha_i L}\right)\eta_i V_{ph} I}{\alpha_i L\left(V_0 + IR_s\right)^2}, \quad (31)$$

and the equation specifying C is

$$C^2 = \frac{1}{qA}\frac{\left(1-e^{-C\kappa_0 L}\right)}{\left(1 - e^{-C\kappa_0 L} - C\kappa_0 L e^{-C\kappa_0 L}\right)} \times \frac{C\kappa_0 L}{\left(V_0 + I\kappa_0/\left(qAC\right)\right)}. \quad (32)$$

This equation can be solved numerically. However, to make more transparent the implications of this expression, it is useful to make a simplifying assumption:

$$e^{C\kappa_0 L} \approx 1 + C\kappa_0 L + \frac{1}{2}\left(C\kappa_0 L\right)^2. \quad (33)$$

TABLE I
PARAMETERS USED FOR FOR NUMERICAL EXAMPLES

Symbol	Definition	Value
λ	Wavelength	1.53 μm
V_{ph}	Photon voltage	0.81 V
V_0	Turn-on voltage	0.84 V
η_i	Internal quantum efficiency	0.97
L	Device length	1.5 mm
w	Device width	0.1 mm
A	Device area	0.15 mm^2
R_1	Mirror reflectivity 1	0.98
R_2	Mirror reflectivity 2	0.07
α_m	Distributed mirror loss	8.9 cm^{-1}
α_c	Constant intrinsic loss	0.1 cm^{-1}
R_c	Constant series resistance	20 mΩ
I_{th}	Threshold current	350 mA

Using this partial Taylor expansion in (32), the solution for the doping magnitude is

$$C \approx \sqrt{\frac{\left(2/L\right)I}{qAV_0}}. \quad (34)$$

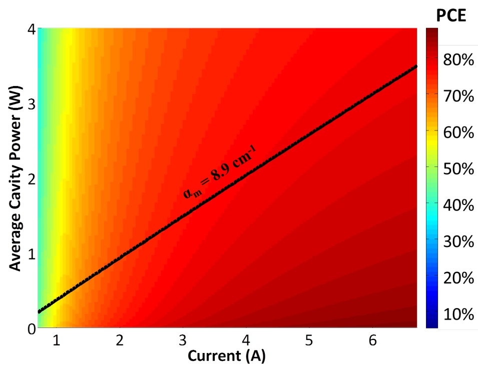
Interestingly, this result is very similar to that for the semiconductor laser in (18). In fact, this equation suggests that the optimized doping level for a high-power SOA is exactly the same as that for a laser with $\alpha_m = 2/L$. The significance of this $2/L$ mirror loss value does not, at present, seem clear.

V. Discussion

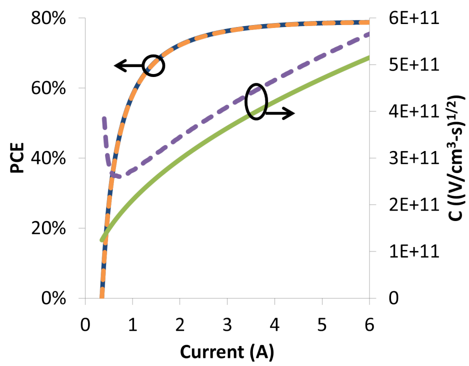
In this section, the expressions of III.*A* and III.*B*. are used in numerical examples to illustrate some of the important features of the doping optimization. The device chosen for analysis is similar to that in [2], whose κ_0 is estimated to be on the order of 10^{-12} (V-cm-s)$^{1/2}$, and the assumed laser parameters are summarized in Table I.

To begin, a comparison of this work's results with those of Kanskar *et al.* is presented. In this case, α_c and R_c are assumed to be zero, since the work of Kanskar *et al.* does not explicitly include these losses. As mentioned in a previous section, one must be careful when using (20), since self-consistency must be maintained between I and P_o. In particular, the expression $P_o = \eta_i V_{ph}\left(I - I_{th}\right)/\left(\alpha_m + \alpha_i\right)L$ must be satisfied. In this case, if η_i, V_{ph}, and I_{th} are maintained approximately constant by material properties, then α_m must be adjusted according to this prescription (α_i cannot be freely adjusted because it is fixed by the optimization procedure). Generally speaking, it is of greater utility to have a specified α_m rather than a specified P_o, since α_m is more directly controlled and measured. Then, as shown in Fig. 1a, one must search the two-dimensional I-P_o space for the one-dimensional line specifying a fixed α_m. This approach is a more complicated analysis than is strictly necessary and, as such, could often be less desirable.

Moreover, the fact that the target expression for optimization is an absolute power loss rather than an efficiency results in a value for C that differs from the optimum for maximum PCE. This can be seen in Fig. 1b, where the results from the constant



(a)



(b)

Fig. 1. (a) The maximum PCE calculated by using (20) as a function of I and P_o. The line of constant $\alpha_m = 8.9$ cm^{-1} is indicated by a solid line. (b) The values of PCE and C for the line of constant α_m in (a) (dashed) and for the solution provided by (18) (solid).

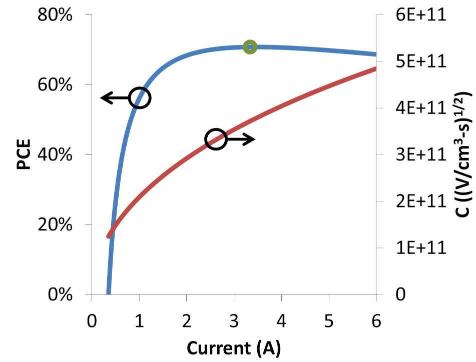


Fig. 2. PCE and corresponding doping level (C) for optimally doped lasers with $\kappa_0 = 10^{-12}$ (V-cm-s)$^{1/2}$ for different applied current as prescribed by (25). The circle indicates the peak PCE found for the doping magnitude in (26).

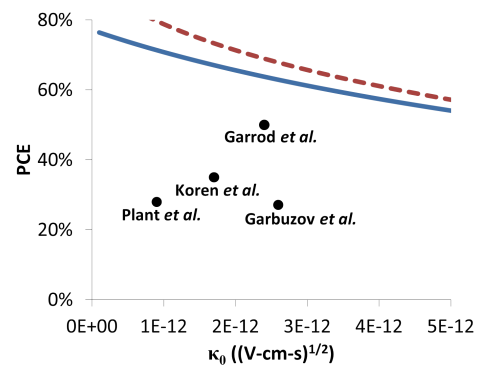


Fig. 3. Peak PCE for optimally doped lasers as a function of κ_0. Solid line represents PCE with α_c and R_c and dashed line represents PCE without them.

α_m line in Fig. 1a are compared with those using (18). In the case presented here, the different expression results in a negligible difference in PCE, at most on the order of 0.1%. Nevertheless, as will be shown shortly, the difference could be more significant for different designs, such as those with larger values of κ_0 or nonzero values of α_c and R_c.

The laser parameters, including the nonzero values of α_c and R_c, are now inserted in (25) and evaluated as a function of the operating current. From this, the optimal doping level is determined, as well as the corresponding PCE. Fig. 2 illustrates the results. As the operating current is increased, the doping level also increases. Intuitively, this occurs because R_s becomes a more significant power loss as current increases, since it goes as the current squared. The PCE experiences a rapid growth above I_{th} and then more gradually increases. The PCE reaches a maximum, as solved for in (26), at the current corresponding to the peak PCE. This is shown as a circle in Fig. 2. After that point, the PCE decreases because of the increased losses associated with the electrical resistance. When Fig. 2 is compared with Fig. 1b, it is evident that the case with nonzero α_c and R_c can have a significantly lower PCE at high currents, in this case about 10%.

As pointed out earlier, κ_0 determines *a priori* the peak achievable efficiency of a laser. The lower the value of κ_0 is, the higher PCE one can expect to achieve. This is illustrated in Fig. 3, where the peak PCE for the chosen example is plotted as a function of κ_0. The peak PCE increases as κ_0 decreases, and the PCE approaches a limit as κ_0 goes to zero, in this case approximately 80%. This maximum PCE is limited by the other sources of losses not targeted by the doping optimization, such as α_c and R_c, voltage defect, and η_i. For reference, estimated κ_0 values and realized PCEs are included in Fig. 3 [14], [15], [16], [2]. All of these points are below the optimum limit represented by the solid line, which suggests that further optimization of doping or other properties could be implemented in these devices. For example, no rigorous procedure appears to have been used to optimize the doping in [14], [15], [16], and so it is reasonable to expect that is, in at least part, an explanation for their PCE values lying far below the limit. In contrast, the authors of [2] did attempt a doping optimization based on the procedure in [3] and have a PCE result not too far below the limit.

Finally, for any realistic device, it is important to understand the performance sensitivity to deviations of the doping level from the optimum, *i.e.*, to what precision must C be realized in order to experience the benefits of the optimized doping profile. This result is shown in Fig. 4 for the case where α_c and R_c take on the values in Table I. Here the peak PCE is plotted as a function of the doping level for three different values of κ_0. In all three cases, the optimum value of C is on the order of 10^{11} (V/cm^3-s)$^{1/2}$ (note the x-axis is on a

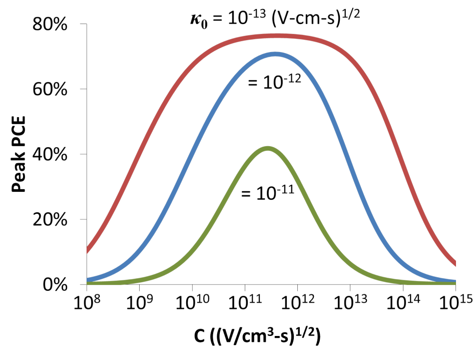


Fig. 4. Peak PCE as a function of doping magnitude, C, for three different values of κ_0.

logarithmic scale). When κ_0 is high, not only is the PCE limited to a much lower value as shown in Fig. 3, but also the range of C over which the PCE is near optimal is small. As κ_0 is decreased, the peak PCE increases to the maximum possible and the tolerance for error in C becomes much larger. For example, as shown in Fig. 4 for $\kappa_0 = 10^{-13}$ (V-cm-s)$^{1/2}$, the doping magnitude can be too large or too small by nearly an order of magnitude before one sees a significant degradation in peak PCE. This emphasizes the importance of having a waveguide design optimized for high PCE and the benefit of having a figure of merit by which one can quantify the waveguide quality.

VI. Conclusion

In this paper, a generalized theoretical formalism has been derived that optimizes the doping profile of semiconductor diode lasers and amplifiers for maximum PCE by balancing resistive and FCA losses. The doping profile has been shown to be the same function of optical mode profile, FCA cross-section, and carrier mobility, independent of the specific model used for efficiency. The magnitude of the doping is dictated by the actual efficiency model and device operating conditions. The maximum PCE is actually determined by the waveguide quality, which has been shown to be measurable using a general figure of merit. Specific examples of optimized PCE have been derived for both lasers and amplifiers, and the impacts of different parameters of laser waveguides and doping have been explored.

The main results of this analysis are contained in (7) and (11). The first expression gives the optimal doping profile to maximize PCE for a particular waveguide design. The latter represents a metric that quantifies a waveguide's ability to achieve high PCE by allowing low FCA and ohmic losses. By using this doping design rule in (7) and optimizing waveguide structures with the figure of merit in (11), it should be possible to make improvements to diode laser and amplifier PCE in any material system and frequency regime.

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